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(54) Closed-loop non-invasive oxygen saturation control system.

(57) An adaptive controller for delivering a fractional amount of oxygen to a patient. The controller utilizes an oximeter coupled by a non-invasive sensor to the patient for measuring the blood hemoglobin saturation in the patient. The oximeter generates a plurality of blood saturation output signals over a given period of time which are sequentially representative of the patient's blood hemoglobin saturation. A processing means evaluates a plurality of the oximeter output signals and, based on the evaluation, provides a pseudo blood saturation signal. A feedback control means responsive to the pseudo output signal sets the fractional amount of oxygen to be delivered to the patient. When deviations of the oximeter output signal are excessive, the pseudo output signals cause a gradual increase in the fractional amount of oxygen for the patient. Furthermore, the feedback control means is periodically disconnected, and the response of the patient to random changes in the fractional amount of oxygen delivered to the patient is used to adapt the response characteristics of the feedback control means in a manner tailored to the needs of the patient.
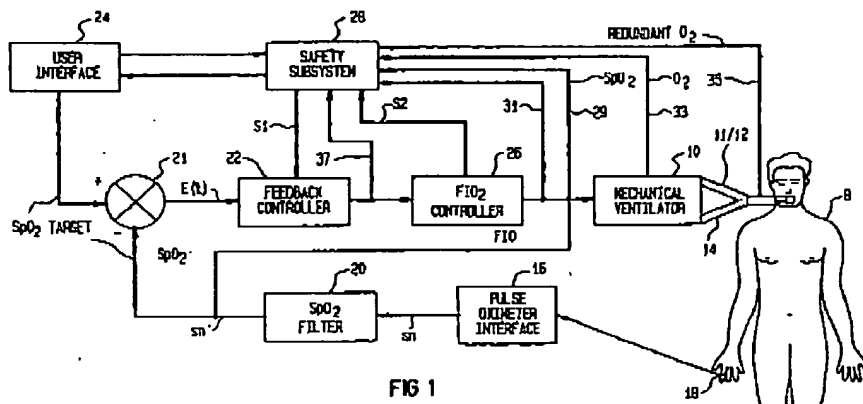
FIG 1

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PAGE 5/28 * RCVD AT 3/14/2007 4:31:37 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-1/13 * DNIS:2738300 * CSID:6123051228 * DURATION (mm-ss):08-36

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BACKGROUND OF THE INVENTION

1. Field of the Invention

5   The present invention relates to automatic control of blood oxygen saturation (S_aO_2) in a patient by adjustment of the fractional amount of oxygen inspired (FIO_2) by the patient, and more particularly, to a feedback control loop for a mechanical ventilator including a non-invasive S_aO_2 monitor in the feedback path for developing an adaptive control signal which controls the inspired gas blender of the ventilator.

10   2. Description of the Prior Art

Devices for controlling the oxygen content of the blood by controlling the fraction of oxygen breathed by a patient are well known. For example, U.S. Patent No. 2,414,747 issued to Harry M. Kirschbaum on January 21, 1947 shows a method and apparatus for controlling the oxygen content of the blood of living
15 animals which discloses control of blood oxygen content by the use of an ear oximeter which produces a signal used to control the proportion of inspired oxygen. As the oximeters direct a beam of light through a capillary bed in the ear, the characteristics of the light become modified by the color of the blood that intercepts its path. Thus, the change in oxygen levels of the blood are detected non-invasively and electrical signals are generated, amplified and used to control the oxygen supply delivered to a patient.
20   Numerous improvements have been made since that time wherein better matching of oxygen delivery to the needs of the patient have been made such as shown in U.S. Patent No. 3,734,091 to Ronald H. Taplin issued on May 22, 1973. Taplin discloses an optical oximeter and a temporary oxygen-deficient mixture (anoxic) to control blood oxygen saturation. Thus, to prevent excessive oxygen levels, Taplin discloses limiting the inspired oxygen by intermittently providing the anoxic mixture each time the oxygen
25 saturation of the blood reaches a predetermined percentage level.

U.S. Patent 4,889,116 issued to Taube on December 26, 1989 discloses one type of adaptive controller for adjusting the fraction of oxygen inspired by a patient. The controller utilizes a pulse oximeter connected by an optical sensor to the patient for measuring the patient's blood hemoglobin saturation (S_pO_2) and pulse rate. These signals from the oximeter are used by a calculator for determining the fractional amount of
30 oxygen to be inspired by the patient. The calculated percentage of oxygen is provided to the patient so that the gas taken in by the patient automatically causes the blood in the patient to reach a predetermined hemoglobin saturation level in response to the patient's requirements as determined by changes in the S_pO_2 signal. However, the calculator is programmed to determine when there is an excess deviation of the patient's pulse rate, thereby indicating patient movement and the probability that the pulse oximeter will
35 provide false S_pO_2 values during such patient movement. When an excess deviation in pulse rate is detected, the fractional amount of inspired oxygen is no longer responsive to the measured S_pO_2 value, but instead held constant until the excess deviation of the pulse rate has been terminated. Furthermore, a low S_pO_2 value, indicative of a depressed respiration (apnea) is also detected, and used to cause a preset higher percentage of inspired oxygen to be supplied to the patient until the depressed respiration of the
40 patient has been terminated. Thus, responsive FIO_2 adjustment is suspended during patient movement and apnea, and during this time fixed FIO_2 levels are set.

In 1980, H. Katsuya and Y. Sakanashi published an article in the Journal of Clinical Monitoring 1989; 5:82-86 describing a method for evaluating pulmonary gas exchange using a pulse oximeter. They developed the concept of FI_{9x} (where x is a single digit number) which is the fraction of inspired oxygen
45 necessary to achieve a measured blood oxygen saturation equal to the value of 9x% (e.g. 98%). This experiment was carried out by periodically manually increasing or decreasing the FIO_2 control of a gas blender portion of a ventilator until the S_pO_2 measurement reached the target percentage (e.g., 98%). The purpose of this experiment was to develop a diagnostic method to evaluate pulmonary gas exchange impairment. A high value of FI_{9x} was associated with poor pulmonary gas exchange. In this publication, no
50 mention was made of feedback of S_pO_2 values for automatic adjustment of FIO_2. The present invention recognizes that the pulmonary impairment of a patient can often change during treatment, thereby requiring a change or adaptation of the responsiveness of the FIO_2 control loop.

Since adult and neonatal patients in intensive care units suffering from respiratory distress are at risk for developing hypoxemia or oxygen toxicity, certain safety precautions should be taken to prevent O_2
55 under/overdose. In an attempt to maintain organ normoxia, appropriate clinical care often mandates ventilation with high FIO_2, sometimes for several days. Long exposure to high concentrations of oxygen has been implicated in complications including exacerbation of respiratory distress and various central nervous system symptoms. In neonatal patients, oxygen toxicity may result in blindness from retrolentalfibroplasia.

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Thus, care should be taken to minimize the FIO_2 exposure while maintaining adequate S_pO_2. so that the onset of these insidious complications can be delayed or avoided. Furthermore. artifacts (false output measurements) are commonly found in the pulse oximeter output due to patient movement and/or low blood profusion in the area where the patient contacts the pulse oximeter sensor. Additionally, it is difficult
5 to actually know what the arterial blood oxygen saturation percentage is from the S_pO_2 (pulse oximeter) measurement. Thus, careful construction of the S_pO_2 feedback control system is required.

It is an object of the present invention to provide a method and apparatus which minimizes the FIO_2 of a patient while maintaining adequate S_aO_2 levels.

It is a further object of the invention to provide artifact rejection processing of the pulse oximeter which
10 is tolerant of the expected false readings of S_pO_2, and furthermore; which is adaptive so as to gradually cause the FIO_2 to increase as the frequency of the artifacts increases.

It is still a further object of the invention to provide an FIO_2 feedback control loop which has a response (transfer characteristic) which is adaptive to the changing requirements of the patient.

It is an even further object of the invention to provide a safety sub-system for the FIO_2 control system
15 in order to prevent a failure in the feedback control system from causing injury to the patient due to extremely inappropriate levels of FIO_2.

SUMMARY OF THE INVENTION

20   In accordance with the principles of the present invention, a method and apparatus is provided for evaluating the oximeter S_pO_2 measurements for artifact rejection purposes, and furthermore, causing a gradual increase in FIO_2 as the frequency of S_pO_2 artifacts increases.

In accordance with a further feature of the invention, a safety sub-system is provided which monitors the output signals from various portions of the FIO_2 control system for correlation and/or excursion beyond
25 preset threshold values. Signals which exceed the thresholds or which do not correlate, cause safety sub-system to indicate an alarm condition to the physician.

In accordance with further features of the invention, a feedback control means of the FIO_2 control loop has an adaptively adjustable response. In the preferred embodiment, the feedback control means comprises a proportional, integral. derivative controller wherein the coefficients of the P, I, D, terms are selectively
30 adjustable in order to provide appropriate respiration therapy to the patient. Additionally, these coefficients may be modified by input signals which are not part of the FIO_2 control loop, such as minute ventilation, tidal volume, etc. Finally, the controller response can be adaptive to the needs of the patient, by periodically disabling the controller and monitoring the response of the patient to random fluctuations of FIO_2. An evaluation of the response of the patient is used to adapt the response characteristic of the feedback
35 controller.

Other features and advantages of the invention will be apparent from the description of the preferred embodiment and from the claims.

For a fuller understanding of the present invention. reference should now be made to the following detailed description of the preferred embodiment of the invention and to the accompanying drawings.
40

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates a schematic representation of a closed-loop S_pO_2 control system constructed in accordance with the present invention for controlling the fractional amount of the inspired oxygen for a
45 patient;
Figure 2 is a block diagram of the flow control algorithm used for artifact rejection in the output signal from the pulse oximeter shown in Figure 1;
Figure 3 is a block diagram of a digital PID controller used in the feedback control system of the present invention;
50 Figure 4 is a block diagram of the computational process of the PID controller of Figure 3.
Figures 5(a) to 5(e) are graphical representations of the non-linear operation of the PID controller of Fig. 3;
Figure 6(a) illustrates a block diagram of the PID controller transfer function in the Laplace domain and Figure 6(b) illustrates a range of values for K3, a term in the controller transfer function; and
55 Figures 7(a) and (b) illustrate a block diagram and waveform useful for understanding the RLS method.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

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Figure 1 illustrates in functional block diagram form a preferred embodiment of the present invention. A substantial portion of functions described below are actually carried out by the control system computer, which will be described later on with respect to the user interface. A patient 8 requiring mechanical ventilation is connected to a mechanical ventilator 10 via a breathing circuit 11. Breathing circuit 11 includes
5 an inspiration line 12 by which ventilation gases are unidirectionally delivered to patient 8 and an expiration line 14 for causing unidirectional flow of expired gases from patient 8 to mechanical ventilator 10. Ventilator 10 may comprise any of several well known types of commercially available mechanical ventilators, such as the Model 900C manufactured by Siemens Corporation and available from Siemens Medical Systems, Iselin, NJ. A pulse oximeter 16 of conventional design includes an optical sensor 18 coupled to the finger of
10 patient 8 for non-invasively (e.g., optically) providing a measurement S_pO_2, in a well known manner, of the blood oxygen saturation level of patient 8. Pulse oximeter 16 may be, for example, of the type manufactured by Siemens Corporation and comprise the Model 961 monitor system including a pulse oximeter cartridge unit therein. Pulse oximeter 16 includes an output for providing a high speed serial digital signal output S_pO_2 representative of the measured S_aO_2 level.
15 Before the measured S_pO_2 level can be used for controlling the FIO_2, certain precautions must be taken. The present inventor has recognized the importance of providing artifact rejection filtering techniques to the measured S_pO_2 level, in order to prevent erroneous operation of the FIO_2 feedback control system. That is, it is normal during the operation of a pulse oximeter, that artifact (false) output information will occasionally be generated in response to e.g., physical movement of patient 8 and/or low profusion in the
20 area of sensor 18. This factor was noted in the forenoted Taube patent, however, responsive FIO_2 control was suspended during patient movement. However, in the present invention, an S_pO_2 artifact filter 20 is provided for processing the output of pulse oximeter 16. In the preferred embodiment, the function of filter 20 is provided completely by software processing in the control system microprocessor. An algorithm is used which rejects artifactual measurements of S_pO_2 based on the statistics of past measurements of S_pO_2.
25 The algorithm replaces measured values of S_pO_2 which fall substantially outside the variance of previous values of S_pO_2 with pseudo values. These pseudo values are related to the average S_pO_2 values and, in accordance with a further aspect of the present invention, the frequency of the artifactual S_pO_2 values. As the frequency of artifacts increases the pseudo values are made increasingly less than the mean value, thereby causing the FIO_2 to be gradually increased. Thus, the algorithm provides an adaptive filtering of the
30 S_pO_2 values and gradual increase in the FIO_2, based on the frequency of the detected artifacts. Details of filter 20 will be described later on in conjunction with Figure 2.
After appropriate artifact rejection filtering, the S_pO_2 value is then compared with a target S_pO_2 value in a comparator 21 and the difference signal E(t) (error) is then applied to a feedback controller module 22. The target S_pO_2 value is provided by a user interface 24 which may comprise a personal computer of
35 conventional design programmed in the C software language and which includes a keyboard, display, microprocessor and data storage means. The system user will input, via the keyboard, the desired set-point and limit values for the blood oxygen saturation levels as well as other patient data. The user interface display provides data to the physician informing him/her of the status of the system, the S_pO_2 set-point, the measured S_pO_2 and the measured FIO_2.
40 Feedback controller 22 may comprise a PID (Proportional-Integral-Derivative) controller, such as described in greater detail later on. Feedback controller 22 receives the error signal provided by comparator 21 and produces a stable control signal in response thereto, having a zero steady state error and limited overshoot. In a preferred embodiment of the invention, the proportional, integral and/or derivative terms are selectively controllable for adapting the response of controller 22. Feedback controller 22 is also adaptive as
45 a function of external input signals, such as minute ventilation (the amount of gas breathed by a patient in one minute). Additional novel features of feedback controller 22 will also be described later on relating to the periodic introduction of random FIO_2 level changes, which are used to adapt the response of the feedback compensation. Feedback controller 22 provides an output which indicates what the FIO_2 level should be, e.g., 30%.
50 An FIO_2 controller 26, comprised partly of software and partly of hardware including a stepper motor, calculates the present set-point of the FIO_2 being delivered to the patient, compares this with the instructions received from feedback controller 22, and then mechanically controls a gas blender included in mechanical ventilator 10 for causing the FIO_2 level to be adjusted. The gas blender, not specifically shown, is a conventional part added to or built-in to mechanical ventilator 10 which controls the mixing of gas from
55 an air source and an O_2 source, respectively, to the gas input of ventilator 10. For example, assume that feedback controller 22 provides an output (in software) to FIO_2 controller 26 demanding that the FIO_2 be increased to 30%. The software portion of FIO_2 controller 26 will then calculate a number of pulses, e.g., 30 to the right, that must be applied to the stepper motor in order to cause the gas blender of mechanical

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ventilator 10 to cause a 30% mixture between O_2 and air. This mechanical connection is indicated by the output from controller 26 to mechanical ventilator 10, although an electronic control could also be used.

A final portion of the invention comprises safety sub-system 28. A series of safety features are implemented in hardware and software which comprise safety sub-system 28 to prevent hypoxic inspired
5 mixtures and inadvertent errors in the operation of the FIO_2 control system. These include:
1. Limit (threshold) values of S_pO_2 and FIO_2 are entered into the system by the user via interface 24. Safety sub-system 28 monitors the artifact corrected S_pO_2 value via line 29, the FIO_2 output from controller 26 via line 31, and the actual O_2 level sensed in ventilator 10 and inspiration line 12 via lines 33 and 35, respectively. Excursions beyond the pre-set thresholds are detected by sub-system 28 and
10 cause visual and audible alerts to be directed to the physician.
2. The system resets (see 4 below) based on missing signals from pulse oximeter 16 or ventilator 10.
3. The system detects error between desired FIO_2 (i.e., the output from controller 22 via line 37) and the measured FIO_2 at three different places. The first place is the output of controller 26 via line 31, the second place is the O_2 indication signal which is provided from mechanical ventilator 10, via line 33 and
15 the third place is a redundant O_2 indication signal provided from an O_2 sensor in breathing circuit 11, via line 35. Each of these values should be correlated; if not, an alarm condition is indicated.
4. The system automatically sets the output of controllers 22 and 26 to 100% when any of the above signals indicate error, via set lines S1 and S2 which are coupled to controllers 22 and 26, respectively, from safety sub-system 28.
20 5. All data is stored on magnetic media for retrospective analysis.
Next, details of artifact filter 20 will be described in conjunction with Figure 2. This filter algorithm is intended to handle artifacts in a safe, i.e. conservative, manner. Firstly, it recognizes that the pulse oximeter is artifact prone because it is sensitive to both patient movement and blood perfusion in the area of sensor 18. Secondly, it assumes that when data is missing or suspiciously different (e.g., low) compared to the
25 date immediately preceding it, it is probably artifactual. When artifacts are occurring, the worst scenario is that the S_pO_2 is actually falling, and increasing the patient FIO_2 would be the appropriate therapy. Thus, when artifacts are occurring, we want to balance our concern that the S_pO_2 may be falling with the knowledge that missing data is a routine occurrence. Furthermore, as the frequency of missing data increases, our concern that S_pO_2 might be falling should also increase. Thus, in accordance with a further
30 aspect of the present invention, when S_pO_2 data is missing or suspiciously low (e.g., more than two standard deviations away from the mean of the previous values) we will initially assume the true S_pO_2 value is likely to be the mean value. Additionally, in accordance with still a further aspect of the invention, to be conservative we will subtract an adaptive factor from the mean value to recognize the potential that the actual S_pO_2 value may be falling. The factor is adaptively increased as the frequency of occurrence of the
35 artifacts increases. This results in progressively increasing levels of FIO_2 for the patient to be set by the FIO_2 control system.

The artifact rejection algorithm of filter 20 is designed to insure that the FIO_2 control system operates normally. As artifacts occur, the control system will tend to increase FIO_2 gradually. Thus, as the frequency of artifacts increases, the controller will drive FIO_2 up harder. When the frequency of occurrence of the
40 artifacts exceeds an intolerable limit, an alarm will sound and the controller will go open loop with FIO_2 = 100%.
As shown in Figure 2, filter 20 operates in accordance with the following process:
Step 202:   Evaluate the S_pO_2 values for artifacts,
Step 204:   Determine the frequency of occurrence for the artifacts, and
45 Step 206:   Adapt the pseudo S_pO_2 control value in accordance with the artifact occurrence frequency.
This process is accomplished as follows:

Step 202

50 As shown in Figure 1, S_n = current S_pO_2 value from pulse oximeter 16. S'_n = S_pO_2 value sent to comparator 21.
S_{n-m} , ..., S_{n-3} , S_{n-2} , S_{n-1} , S_n is a series of m past S_pO_2 output values.
Compute a running average of S_{n-m} as:

55

$$S_n = \left(\sum_{i=n-m}^{n-1} S_i \right) \div m$$

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Compute a standard deviation of S_{n-m} as:

$$S_n = \left(\frac{\sum\limits_{1=n-m}^{n-1} (S_i)^2 - ((\sum\limits_{1=n-m}^{n-1} S_i)^2) \div m}{m-1} \right)^{\frac{1}{2}}$$

Then, let M_n = a binary logical variable (possible artifact). We then set up four tests (windows) to determine if M_n is TRUE, i.e., an artifact, or FALSE, i.e., probably not an artifact but a good S_pO_2 value from oximeter 16.

1. If $S_n < (S_n - 2S_n)$ and $S_n > 2$ then M_n = TRUE
2. If $S_n < (S_n - 4)$ and $S_n \leq 2$ then M_n = TRUE
3. If $S_n \geq (S_n - 2S_n)$ and $S_n > 2$ then M_n = FALSE
4. If $S_n \geq (S_n - 4)$ and $S_n \leq 2$ then M_n = FALSE

As you can see from tests 1 and 3, if the standard deviation is greater than 2, it is relatively safe to say that if S_n is less than two standard deviations from the running average value, it's probably artifactual, and if S_n is not less than two standard deviations from the running average, it's probably valid. For example, if the running average = 96% and the standard deviation is 3%, if the current S_n is less than 90%, it's assumed to be an artifact and if equal to or greater than 90%, it is assumed to be valid.

Tests 2 and 4 are intended for the case where the standard deviation is small, i.e. less than or equal to 2%. Under these circumstances it would be difficult to use standard deviation as a measure of validity since even slight changes can be erroneously considered artifacts. Thus, under these circumstances, a fixed change in S_n from the running average is used as the validating criteria. In the preferred embodiment, the fixed amount is a 4% change. For example, if the running average was 96% and the current S_n was 93%, it would not be considered an artifact. It should be understood that the criteria given here are those currently being used by the inventor, and that future testing may result in modifications of these values and even the use of other criteria, such as the average absolute difference of each value from the mean value.

Step 204

Compute the frequency of artifact occurrences

$$F_n = \frac{\text{number of TRUE } M\text{'s}}{m}$$

for M_i where i = M-m to n-1

Step 206

1. If M_n = FALSE then $S'_n = S_n$
2. If M_n = TRUE then $S'_n = S_n - Q$, where Q is one of q_1, q_2 or q_3.
Where,
   Q = q_1 if $1/m < F_n \leq f_a$;
   Q = q_2 if $f_a < F_n \leq f_b$; and
   Q = q_3 if $f_b < F_n \leq f_c$.
Also:
3. If $F_n > f_c$ then: a) ALARM. b) set FIO_2 = 100%; and c) set S'_n = 0.5% (an arbitrary small, non-zero amount)
4. If $S_n > 1/3 S_n$ then ALARM

In the preferred embodiment, m = 10 sample S_pO_2 values, f_a = 3/10, f_b = 5/10, f_c = 6/10, and q_1 = 0.5%, q_2 = 1.0%, and q_3 = 2.0%.

Feedback controller 22 of the present invention is of the PID (Proportional-Integral-Derivative) controller type, and computes a feedback compensation response which is related to the difference between the desired (set-point) and measured S_pO_2 values i.e., the output of comparator 21. The flow of the O_2 gas which is added to the breathing mixture of the patient is controlled by an electronic signal from controller 22

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which is used to adjust the stepper motor of controller 26. The electronic signal is a function of the sum of three terms:

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$$Y(t) = C_1 \cdot E(t) + C_2 E(t)dt + C_3 \frac{dE(t)}{dt}$$

10   where Y(t) is the flow control signal, C_1, C_2 and C_3 are constants, E(t) is the Error (difference between the desired S_pO_2 and the measured S_oO_2 (S'_n) and dE(t)/dt is the time derivative of E(t). The output Y(t) may be adjusted by a constant of proportionality as circumstance may dictate.

Although the above is an analog implementation of feedback controller 22, it is also possible to use a sampled-data equivalent feedback controller, such as commonly used with microcomputers. The block
15   diagram of a digital PID controller of the preferred embodiment is shown in Figure 3. The transfer function of the digital PID controller is as follows:

$$\frac{Y(nT)}{E(nT)} = K_3 + \frac{K_2T(Z+1)}{2(Z-1)} + \frac{K_1(Z-1)}{TZ}$$

20

The microcomputer of the user interface system samples the input variable (E(t))periodically (every T seconds). Computer software is used to mathematically implement the feedback algorithm of controller 22.
25   While the output of the digital controller is presented every T seconds, a circuit element called a zero-order-hold takes the periodically produced output e(t), holds it steady and implements the controlling output action.

In the block diagram of the digital PID controller in Figure 3, K_3, K_2 and K_1 are coefficients (gain constants) of the proportional, integral and derivative terms, respectively. T is the sample time interval. n is
30   an integer number of sample intervals. Z is the Z-transform operator. E(nT) is the error signal e(t) sampled every T seconds, and Y(nT) is the desired FIO_2 value. Note that K_3, K_2 and K_1 serve the same purpose as C_1, C_2 and C_3 in the analog implementation discussed previously; however, the values of K_1, K_2 and K_3 may be different from C_1, C_2 and C_3.

A block diagram of this process is shown in Figure 4. The values of the coefficients as shown in Figure
35   4 are dependent on the characteristics of the design of the system which is being controlled. The increment (n), error (E), flow (F) and the output are functions of the volume and flow characteristics of the breathing circuit, the patient's lung and O_2 transfer characteristics, and the settings of the ventilator.

It is also possible to use the patient's minute ventilation (MV), title volume (TV), and/or respiratory rate (RR) to modify one or more of the terms in the above circuit equation. The patient's minute ventilation, tidal
40   volume, or respiratory rate may be measured using any of several well-known techniques. For example, these measurements may be based on thermal dissipation, a pressure difference across a resistive element (pneumotachograph), the rotation rate of a vane, or the oscillation frequency of a fluid vortex. This type of modification of the invention will be described next in greater detail with respect to Figure 6. Furthermore, in accordance with another aspect of the invention, design goals such as tolerable overshoot, time to achieve
45   control and accuracy of control are also used to determine the value of coefficients K_1, K_2 and K_3. Details relating to modifications of this type are described in greater detail with respect to Figure 7.

First, however, the initial set-up of controller 22 will be described. Referring to the above equation for the transfer function of the digital PID controller, the values of K_1, K_2 or K_3, or any selective combination of K_1, K_2 and K_3 are adjusted as a function of the error signal e(t), i.e., the output of comparator 21. The initial
50   set-up of these values is accomplished in order to tailor the response of the FIO_2 control system in accordance with the clinical goals for given classes of patients. For example, there may be a first set of values for K_1, K_2, K_3 for adults and a second set of K values for neonatal patients.

In accordance with a further aspect of the invention, these K values of the PID controller are made non-linear in order to more appropriately tailor the response of the FIO_2 system in accordance with empirically
55   determined desired values for specific classes of patients. Additionally, it is noted that the non-linear gain provided by PID controller 22 makes the response of the FIO_2 control loop more clinically appropriate. For example, Figure 5(a) illustrates a value for K_1 as a function of e(t). However, a limiting value is provided so that the integrator term does not get to large. Although the previously noted U.S. Patent 4,889,116 to Taube

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includes a PID controller. it is noted that no individual control of the proportional or integral or derivative terms is provided. such as specifically provided by the present invention.

Figure 5(b) illustrates an additional non-linear characteristics for the K values, which was used for the K_3 value specifically in the preferred embodiment of the present invention and Figure 5(c) is an alternative
5 embodiment thereof. Thus. it is apparent from these figures that non-linear coefficients are provided for various ones of the terms of the PID controller which change in real time in accordance with the error signal provided at the output of comparator 21.

Additionally, it is noted that limiting values are also imposed upon the output of PID controller, as previously noted, which prevent the output FIO_2 values from being greater than 100% or less than 0%.
10 Figure 6(a) is illustrative of the way in which external inputs can be applied to control the coefficients of PID controller 22 in order to change the system response accordingly. The external inputs may comprise the minute ventilation (MV), the respiratory rate (RR) and/or the tidal volume (TV). For example, K_1 could be a function of minute ventilation or K_1, K_2, K_3 could be functions of RR, MV and TV, respectively. In fact, any combination of functional relationships between the K's and external inputs are possible. In the preferred
15 embodiment, the value of K_3 is changed in response to the minute ventilation as shown in Figure 6(b).

A final control of the characteristics for controller 22 relates to an adaptiveness of its response to the changing needs of the patient. In this regard, it is noted that in the forenoted Taube U.S. Patent 4,889,116, the controller program described in Exhibit A initially asks the user to input a "lung time constant tl". The present inventor has recognized that the initial values of k which determine the controller response may not
20 be appropriate during later periods of the ventilation therapy for the patient. In accordance with a further feature of the invention, the PID controller output is periodically and randomly varied (within prescribed safety limits) in order to adapt the responsiveness of controller 22 with the changing needs of the patient.

Figure 7(a) illustrates a functional block diagram of the FIO_2 control loop including a Recursive Least Squares (RLS) computation used for modifying the response of controller 22. When software switch A is in
25 position one, the RLS algorithm 700 is dormant. Under these conditions, the values for the gains of the PID feedback compensation (K_1, K_2 and K_3) are set at their initial (default) values.

When RLS algorithm 700 is activated, switch A is in position two, and a sequence of random magnitude FIO_2 values are applied to the blender of ventilator 10 via line B. The sequence of random FIO_2 values are a percentage ($\pm$) of a predetermined FIO_2 value. The predetermined value is the last value of FIO_2 before
30 the RLS algorithm was started (which is input to RLS algorithm 700 via line C). The initial value may also be an average of several previous FIO_2 values in order to eliminate the possibility that the last FIO_2 value is non-representative of the actual needs of the patient.

Figure 7(b) illustrates an example of what one such random sequence might look like. The random 10 second periods of FIO_2 $\pm m\%$ occur approximately 20 to 60 times each 15 minutes, in the preferred
35 embodiment. The range of amplitudes of m· is set by clinical considerations and performance issues. A range of m equal to 10%, 15% and 20% has been used.

The response of the patient as measured by pulse oximeter 16 is input to RLS algorithm 700 via line D for processing. When the RLS algorithm has collected several values, in the preferred embodiment 30, it begins to process these values in accordance with the Recursive Least Squares (RLS) computation, such as
40 known by those skilled in the art, and described for example in "Dynamic System Identification: Experiment, Design and Data Analysis" by Graham C. Goodwin and Robert L. Payne, Academic press, New York, 1977; and an article entitled "Digital Parameter-Adaptive Control of Processes with Unknown Dead Time" by Kurz et al. in Automatica, Vol. 17, No. 1, pp. 245-252, 1981, published by Permagon Press; and as also described in conjunction with control of arterial blood pressure in an article entitled "The Self-Tuning
45 Controller: Comparison with Human Performance in the Control of Arterial Pressure" by Kenneth S. Stern et al., published in the Annals of Biomedical Engineering.

Briefly, what the RLS algorithm does is find a set of coefficients (a's and b's) of a linear combination of past and present FIO_2 values and past S_pO_2 values for determining an estimated S_pO_2 value, which set of coefficients minimizes the mean square difference between this estimated value of S_pO_2 and the actually
50 measured value of S_pO_2. When values for a and b are obtained which cause the computed and measured values to be substantially equal, it can be said that the RLS algorithm has converged. If 30 samples of S_pO_2 at 10 second intervals was not enough to cause convergence, the RLS algorithm will continue acquiring new S_pO_2 values while dropping the oldest S_pO_2 values and then try to converge. Upon convergence, new values may be found for the time constant (T) and time delay (L) of the controller response, which leads to
55 new values for the K_1, K_2, and K_3, coefficients, respectively. These new coefficients are coupled to controller 22 via line K. A more detailed description of the theory and process for accomplishing the RLS algorithm is described in greater detail in Exhibit A.

Thus, there has been shown and described a novel method and apparatus for controlling the amount of

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oxygen inspired by a patient. Many changes. modifications, variations and other uses and applications of the subject invention will, however, become apparent to those skilled in the art after considering this specification and the accompanying drawings. which disclose a preferred embodiment thereof. For example. the PID controller of the present invention could in fact be a PI controller or some other type of controller
5 having adjustable response characteristics. Furthermore the feedback control loop could be integrated into the ventilator 10 or pulse oximeter 16. All such changes, modifications, variations and other uses and applications of the invention are deemed to be covered by the claims which follow.

Claims

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1. An adaptive controller for delivering a fractional amount of oxygen to a patient, said controller comprising:
    oximeter means coupled by a non-invasive sensor to said patient for measuring blood hemoglobin saturation in the patient, said oximeter generating a plurality of blood saturation output signal values
15   over a given period of time, sequentially representative of said blood hemoglobin saturation:
    processing means responsive to said blood saturation output signal for evaluating a plurality of said output signal values and. based on said evaluation. providing a processed output signal; and
    feedback control means continuously responsive to said processed output signal for determining the fractional amount of oxygen to be delivered to the patient.

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2. The adaptive controller of claim 1 wherein said oximeter is a pulse oximeter and said plurality of blood saturation output signal values are oxygen saturation of hemoglobin values as measured by a pulse oximeter (S_pO_2 values).

25 3. The adaptive controller of claim 1 wherein said processing means includes:
    artifact recognition means for identifying possibly invalid output signal values and for providing a sequence of valid output signal values, exclusive of said identified possibly invalid output signal values; and
    means for generating a running average of said sequence of valid output signal values and for
30   providing said running average as said processed output signal;

4. The adaptive controller of claim 3 wherein said artifact recognition means includes means for comparing each of said plurality of output signal values to said running average and for identifying as possibly invalid any output signal value which differs from said running average by more than a
35   predetermined amount.

5. The adaptive controller of claim 3 wherein the artifact recognition means further includes means for substituting respective pseudo output signal values for each of said identified possibly invalid output signal values to generate said sequence of valid output signal values. wherein the value of said pseudo
40   output signal values is a function of said running average of said oximeter means output signal values.

6. The adaptive controller of claim 5 wherein said processing means further includes:
    monitoring means. coupled to said artifact recognition means, for determining the frequency of occurrence of said possibly invalid output signal values; and
45   means. coupled to said monitoring means, for decreasing the value of said pseudo output signal values in proportion to the frequency of occurrence of said possibly invalid output signal values to condition the feedback control means to gradually increase the fractional amount of oxygen to be delivered to the patient.

50 7. The adaptive controller of claim 3 wherein said means for generating said running average includes means for calculating a mean value and a standard deviation value for m of said plurality of valid output signal values most recently provided by said artifact recognition means, where m is an integer, and for providing said calculated mean value as said processed output signal.

55 8. The adaptive controller of claim 7 wherein said artifact recognition means includes means for comparing each of said plurality of output signal values to said mean value and for identifying as possibly invalid any output signal value which differs from said mean value by an amount greater than two times said standard deviation value.

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9. The adaptive controller of claim 7 wherein the feedback control means includes:
   means for generating a difference signal having a value which represents the difference between the processed output signal and a value representing a desired blood hemoglobin saturation value; and
   means, responsive to said difference signal, for changing the fractional amount of oxygen delivered to the patient in a sense which tends to reduce the value of said difference signal.

10. The adaptive controller of claim 9 wherein the means for changing the fractional amount of oxygen delivered to the patient includes a proportional-integral-derivative controller.

11. An adaptive controller for delivering a fractional amount of oxygen to a patient, said controller comprising:
   measuring means, adapted to be coupled to the patient, for measuring blood oxygen level in the patient and for providing a plurality of output signal values, sequentially representative of said measured blood oxygen level;
   processing means, coupled to said measuring means, for generating a running average of said plurality of output signal values and for subtracting said running average from a target value, representing a desired blood oxygen level for the patient, to produce a difference signal;
   feedback control means, coupled to receive said difference signal, for adjusting the fractional amount of oxygen to be delivered to the patient to minimize said difference signal in magnitude.

12. The adaptive controller of claim 11 wherein the feedback controller is defined by a transfer function, having a plurality of adjustable coefficients, which establishes how the fractional amount of oxygen delivered to the patient is to be changed, both in time and in magnitude, in response to a change in the difference signal.

13. The adaptive controller of claim 12, further including:
   means for measuring a plurality of physiological parameters related to respiration to produce a respective plurality of output signals; and
   adjustment means responsive to said plurality of output signals for adaptively changing the values of said coefficient values to change the transfer function of said feedback controller.

14. The adaptive controller of claim 13 wherein said physiological parameters include one or more of minute ventilation, respiratory rate and tidal volume; and
   said adjustment means includes means for automatically adjusting said coefficient values as a function of said plurality of output signals.

15. The adaptive controller of claim 12 further including means for periodically and automatically varying the coefficient values to change the transfer function of the feedback controller to track changing needs of the patient.

16. The adaptive controller of claim 15 wherein the means for periodically and automatically varying the coefficient values includes:
   means for randomly changing the fractional amount of oxygen to be delivered to the patient within predetermined minimum and maximum limiting values; and
   coefficient adapting means, responsive to the respective measured blood oxygen level values resulting from the changes in the fractional amount of oxygen, for adjusting the coefficient values to match the response of the control system to the response of the patient.

17. The adaptive controller of claim 16 wherein the coefficient adapting means includes:
   means for recording the random sequence of changes in fractional amount of oxygen delivered to the patient and the respective measured blood oxygen levels resulting from the sequence of changes in the fractional amount of oxygen;
   means for calculating, based on the recorded changes in the fractional amount of oxygen, the recorded blood oxygen levels and the transfer function of the feedback controller, an expected present blood oxygen level; and
   means for repeatedly changing the coefficient values and recalculating the expected present blood oxygen level to minimize any difference in magnitude between the expected present blood oxygen level and the measured blood oxygen level currently provided by the measuring means.

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18. The adaptive controller of claim 17 wherein the means for repeatedly changing the coefficient values includes means for evaluating the recorded changes in the fractional amount of oxygen, the recorded blood oxygen levels and the transfer function of the feedback controller according to a recursive least squares optimization method.

19. The adaptive controller of claim 12 wherein the feedback controller is a proportional-integral-derivative (PID) controller.

20. The adaptive controller of claim 19 wherein the transfer function, Y(nT)/E(nT), defining the feedback controller is given by an equation:

$$Y(nT)/E(nT) = K_3 + K_2 T(Z+1)/(2(Z-1)) + K_1(Z-1)/(TZ)$$

where K_3, K_2 and K_1 are respective proportional, integral and derivative coefficient values, Z is the Z-transform operator, T is a sampling interval in seconds. n is the number of current sample values, Y(nT) is the current output value and E(nT) is the current value of the difference signal.

21. In a system for automatically providing a controlled fractional amount of oxygen to a patient, including an oximeter for measuring blood oxygen levels of the patient and a feedback controller, coupled to the oximeter for adjusting the fractional amount of oxygen delivered to the patient to maintain the measured blood oxygen levels within predetermined limits, a safety subsystem to prevent the system from erroneously administering a hypoxic mixture. said safety subsystem comprising:

means for measuring the fractional amount of oxygen being delivered to the patient and for providing a signal indicative thereof;

means for correlating the measured fractional amount of oxygen to a preferred fractional amount of oxygen as determined by the feedback control system and for producing an alarm signal when the measured and preferred fractional amounts of oxygen are determined to be uncorrelated;

means, responsive to said alarm signal, for adjusting the fractional amount of oxygen to be delivered to the patient to a maximum value.

22. The safety subsystem of claim 21, wherein:

the means for measuring the fractional amount of oxygen delivered to the patient includes means for sensing the oxygen level of the air being provided to the patient using a plurality of sensors; and

the correlating means includes means for correlating the preferred fractional amount of oxygen to each of the plurality of sensed oxygen levels and for generating said alarm signal if any of the sensed oxygen levels is not correlated to said preferred fractional amount of oxygen.

23. The safety subsystem of claim 21, further comprising:

first monitoring means for detecting errors in the blood oxygen level signal provided by said oximeter;

second monitoring means for detecting errors in the signal provided by said means for measuring the fractional amount of oxygen being delivered to the patient; and

means for generating said alarm signal in response to an error being detected by one of said first and second monitoring means.

24. The safety subsystem of claim 23 wherein said first and second monitoring means detect missing values of said respective blood oxygen level signal and said measured fractional amount of oxygen signal as the errors in the respective signals.

25. The safety subsystem of claim 21 wherein said feedback controller includes:

means for monitoring the blood oxygen level signals provided by the oximeter to identify possibly invalid signal values and to provide a sequence of valid signal values. exclusive of said identified possibly invalid signal values; and

said safety system further includes:

means for setting a first threshold value representing a minimum desirable level of said blood oxygen level signal and a second threshold value representing a minimum desirable level of said preferred fractional amount of oxygen and said measured fractional amount of oxygen; and

means for producing said alarm signal when one of said sequence of valid signal values is less

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than said first threshold value;
means for producing said alarm signal when one of said preferred fractional amount of oxygen and said measured fractional amount of oxygen is less than said second threshold value.

26. The safety subsystem of claim 21 further comprising, non-volatile memory means for storing the measured blood oxygen level values provided by said oximeter and the measured fractional amount of oxygen being delivered to the patient.

27. The safety subsystem of claim 26 wherein values representing said preferred fractional amount of oxygen are stored in said non-volatile memory means.

28. A method for adaptively controlling the fractional amount of oxygen delivered to a patient comprising the steps of:
a) measuring the blood hemoglobin saturation in the patient during a plurality of intervals over a given period of time and providing said measured values as an output signal;
b) evaluating each of the measured values of said output signal to identify possibly invalid output signal values;
c) eliminating said identified possibly invalid output signal values from said output signal to produce a processed output signal;
d) adjusting the fractional amount of oxygen delivered to the patient in a sense to minimize any difference between said processed output signal and a predetermined desired blood hemoglobin saturation signal.

29. The method of claim 28 wherein the step c) includes the steps of:
c1) generating a sequence of valid output signal values by substituting a pseudo value for each of said identified possibly invalid output signal values;
c2) generating a running average of successive values of said sequence of valid output signal values, wherein the instantaneous value of said running average is said pseudo value; and
c3) providing said running average as said processed output signal.

30. The method of claim 29 wherein step c1) includes the steps of:
monitoring the frequency of occurrence of said identified possibly invalid output signal values; and
decreasing the value of said substituted pseudo values in proportion to the frequency of occurrence of said identified possibly invalid output signal values.

31. A method of adapting an automatic controller which delivers a controlled fractional amount of oxygen to a patient to maintain a measured blood oxygen level at a value which approximates a preferred blood oxygen level, wherein the controller operates in accordance with a transfer function having variable coefficient values, said method comprising the steps of:
a) changing the fractional amount of oxygen delivered to the patient within predetermined minimum and maximum limiting values in accordance with a pseudo-random sequence;
b) measuring the blood oxygen level of the patient resulting from each change in the fractional amount of oxygen delivered to the patient including a final blood oxygen level resulting from a final fractional amount of oxygen in the pseudo-random sequence;
c) recording a sequence of values representing the fractional amounts of oxygen provided in step a) and the respective measured blood oxygen levels obtained in step b);
d) calculating, based on the recorded fractional amounts of oxygen, the recorded blood oxygen levels, exclusive of said final blood oxygen level, and the transfer function, an expected final blood oxygen level;
e) repeatedly changing the coefficient values and repeating step d) to minimize any difference in magnitude between the expected final blood oxygen level and the recorded final blood oxygen level.

32. The method of claim 31 wherein step e) includes the steps of changing the coefficient values and repeating step d) in accordance with a recursive least squares optimization method.
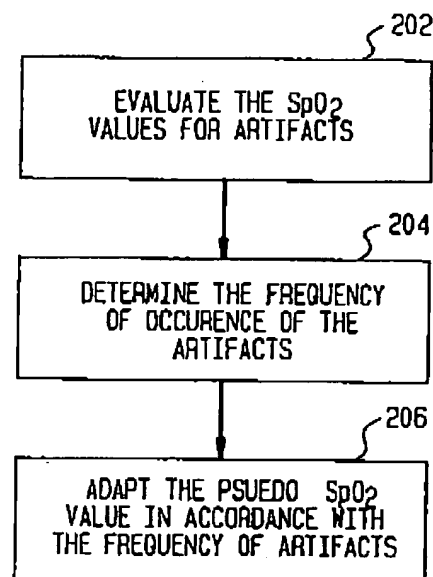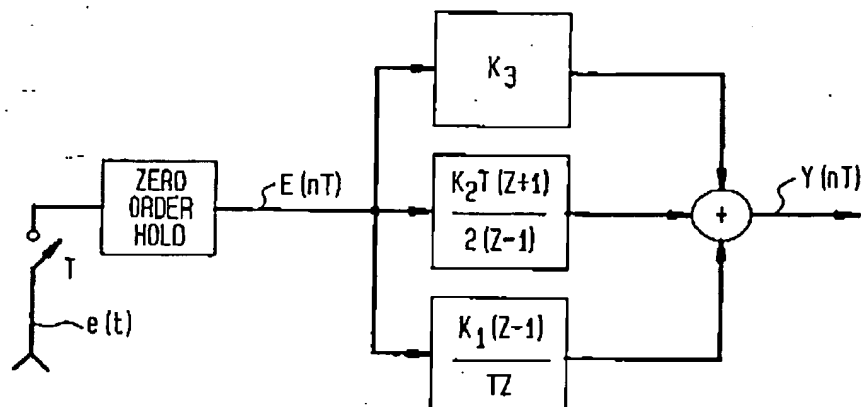
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FIG 1

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FILTER 20
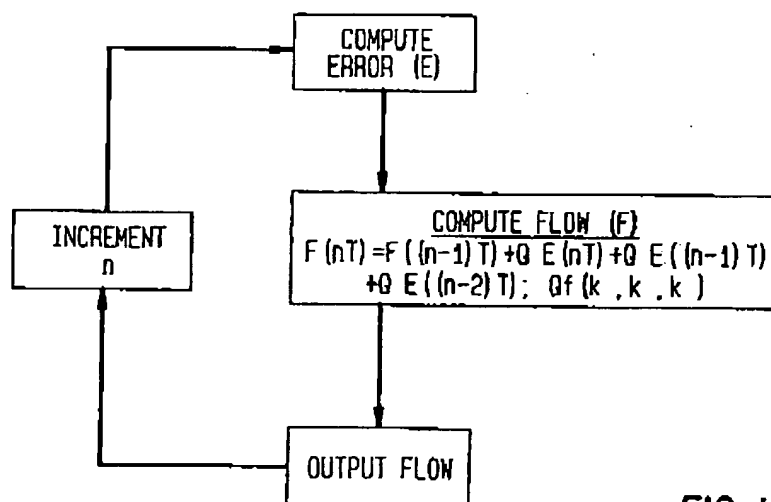
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                                        ┌ 202
        ┌──────────────────────────────┐
        │     EVALUATE THE SpO₂         │
        │     VALUES FOR ARTIFACTS      │
        └──────────────────────────────┘
                       │
                       │                ┌ 204
                       ▼
        ┌──────────────────────────────┐
        │    DETERMINE THE FREQUENCY    │
        │     OF OCCURENCE OF THE       │
        │         ARTIFACTS             │
        └──────────────────────────────┘
                       │
                       │                ┌ 206
                       ▼
        ┌──────────────────────────────┐
        │   ADAPT THE PSUEDO  SpO₂      │
        │   VALUE IN ACCORDANCE WITH    │
        │   THE FREQUENCY OF ARTIFACTS  │
        └──────────────────────────────┘
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FIG 2

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FIG 3

FIG 4

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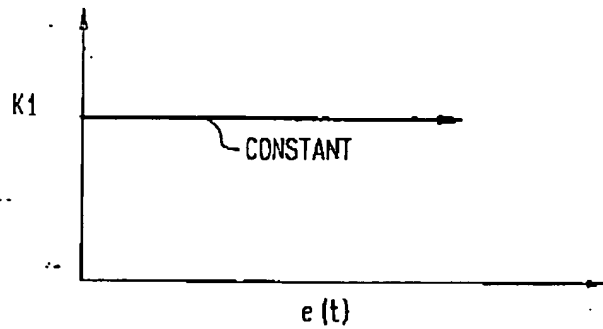
FIG 5a
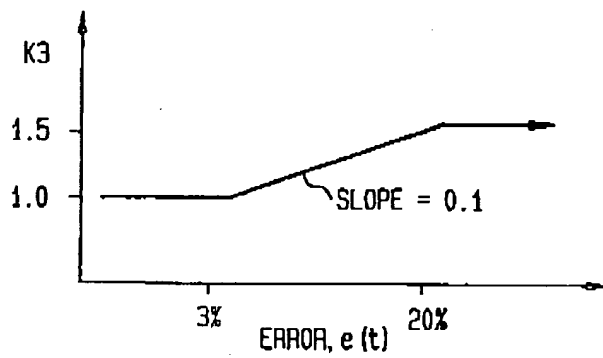
FIG 5b
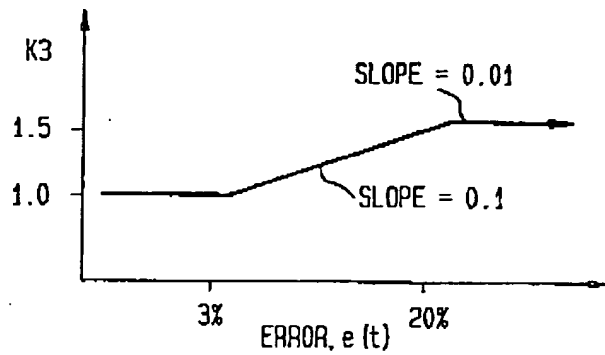
FIG 5c
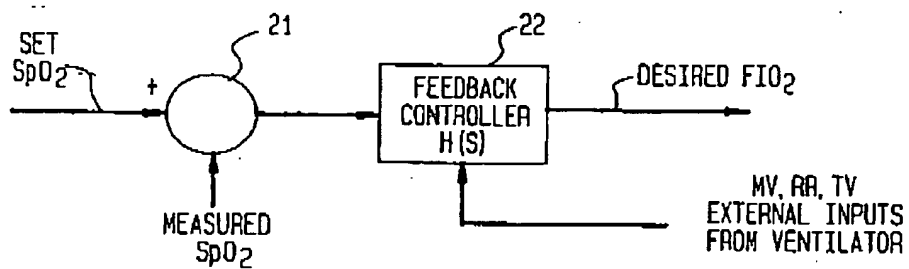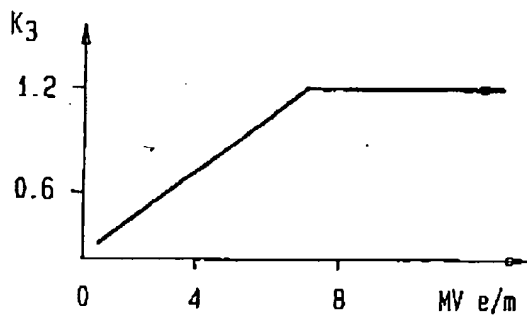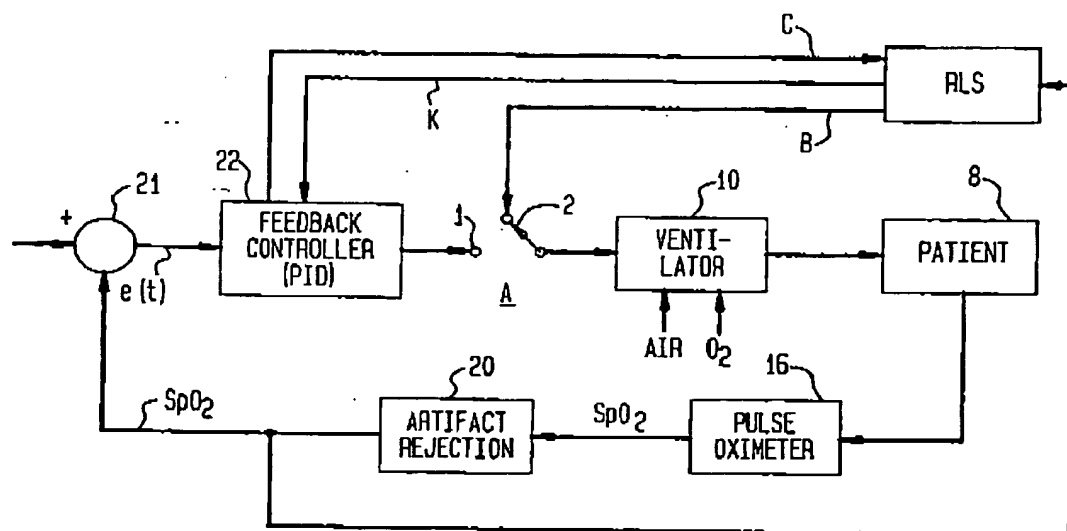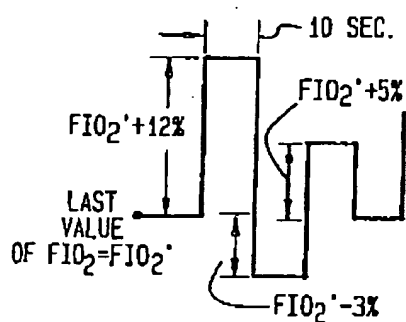
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SET
SpO2

MEASURED
SpO2

FEEDBACK
CONTROLLER
H (S)

21

22

DESIRED FIO2

MV, RR, TV
EXTERNAL INPUTS
FROM VENTILATOR

FIG 6a

K_3

1.2

0.6

0   4   8   MV e/m

FIG 6b

FIG 7a

FIG 7b

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(54) Closed-loop non-invasive oxygen saturation control system.

(57) An adaptive controller for delivering a fractional amount of oxygen to a patient. The controller utilizes an oximeter coupled by a non-invasive sensor to the patient for measuring the blood hemoglobin saturation in the patient. The oximeter generates a plurality of blood saturation output signals over a given period of time which are sequentially representative of the patient's blood hemoglobin saturation. A processing means evaluates a plurality of the oximeter output signals and, based on the evaluation, provides a pseudo blood saturation signal. A feedback control means responsive to the pseudo output signal sets the fractional amount of oxygen to be delivered to the patient. When deviations of the oximeter output signal are excessive, the pseudo output signals cause a gradual increase in the fractional amount of oxygen for the patient. Furthermore, the feedback control means is periodically disconnected, and the response of the patient to random changes in the fractional amount of oxygen delivered to the patient is used to adapt the response characteristics of the feedback control means in a manner tailored to the needs of the patient.
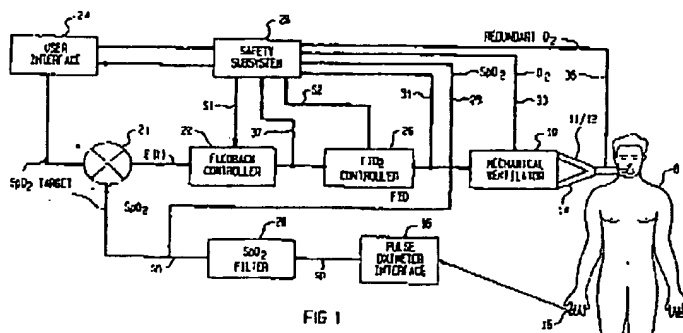
FIG 1

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European Patent
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EUROPEAN SEARCH REPORT

Application Number

EP 92 10 4185

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
Y	IEE PROCEEDINGS vol. 132, no. 5, 24 September 1985, STEVENAGE, GB pages 205 - 211 A.SANO ET AL 'Adaptive control of arterial oxygen pressure of newborn infants under incubator oxygen treaments'	1	A61B5/083 A61B5/097 A61B5/00 A61M16/00
A	* page 205, right column, line 43 - page 208, left column, line 3; figures 1-4 *	2,9, 10-13, 15-19, 28,31	
Y	EP-A-0 303 502 (NATIONAL RESEARCH DEVELOPMENT CORP.)	1	
A	* page 1, line 1 - line 20 * * page 3, line 6 - page 4, line 3; figure 5 *	3,4	
D,A	US-A-4 889 116 (J.C.TAUBE) * column 3, line 28 - column 8, line 19; figures 1,2 *	1,2,9, 11,28	TECHNICAL FIELDS SEARCHED (Int. Cl.5) A61B A61N

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
BERLIN	19 AUGUST 1993	WEIHS J.

CATEGORY OF CITED DOCUMENTS

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